ITPA Topical Group Meeting
JAERI Naka
2004/03/10

SSOEP/TP/CDBM Modeling Joint Session

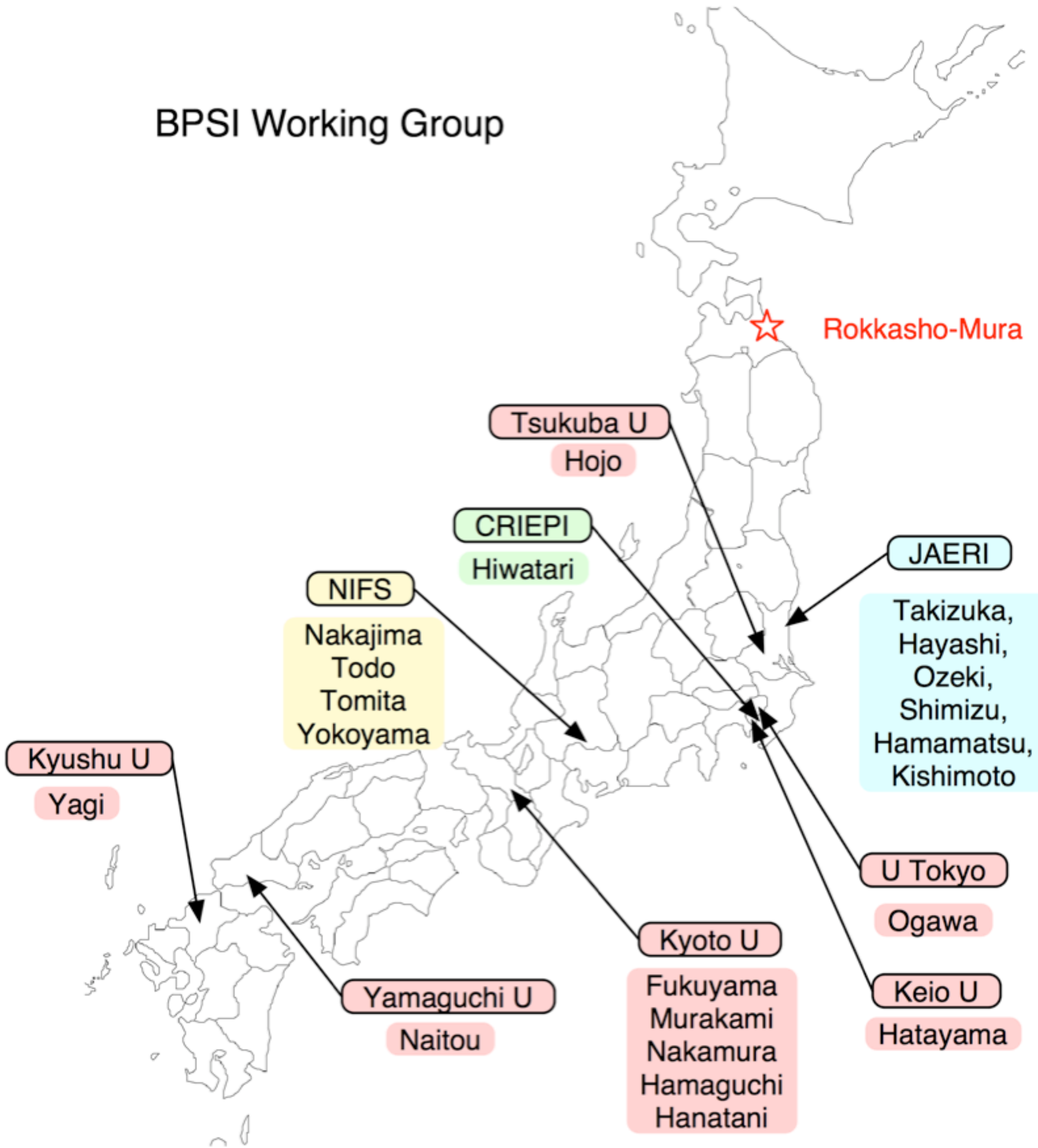
Integrated Code Development for Burning Plasma Simulation

A. Fukuyama, M. Honda (Kyoto U.)
M. Yagi (Kyushu U)

- Burning Plasma Simulation Initiative
- Integrate Code TASK
- Transport Analysis TASK/TR
- Preliminary ITER Plasma Simulation
- Transport Analysis TASK/TX

Burning Plasma Simulation Initiative

Collaboration of Universities, NIFS and JAERI



Activities of BPSI

Framework of Integrated Code:

- Standard interface for data transfer
- Reference core code: TASK

Modeling of Phenomena with Different Scales:

- Transport-MHD hierarchical model
- Core-SOL interface model
- Transport modeling in the presence of islands

Advanced Computational Technique:

- Parallel processing
- Distributed computing
- Visualization

TASK code

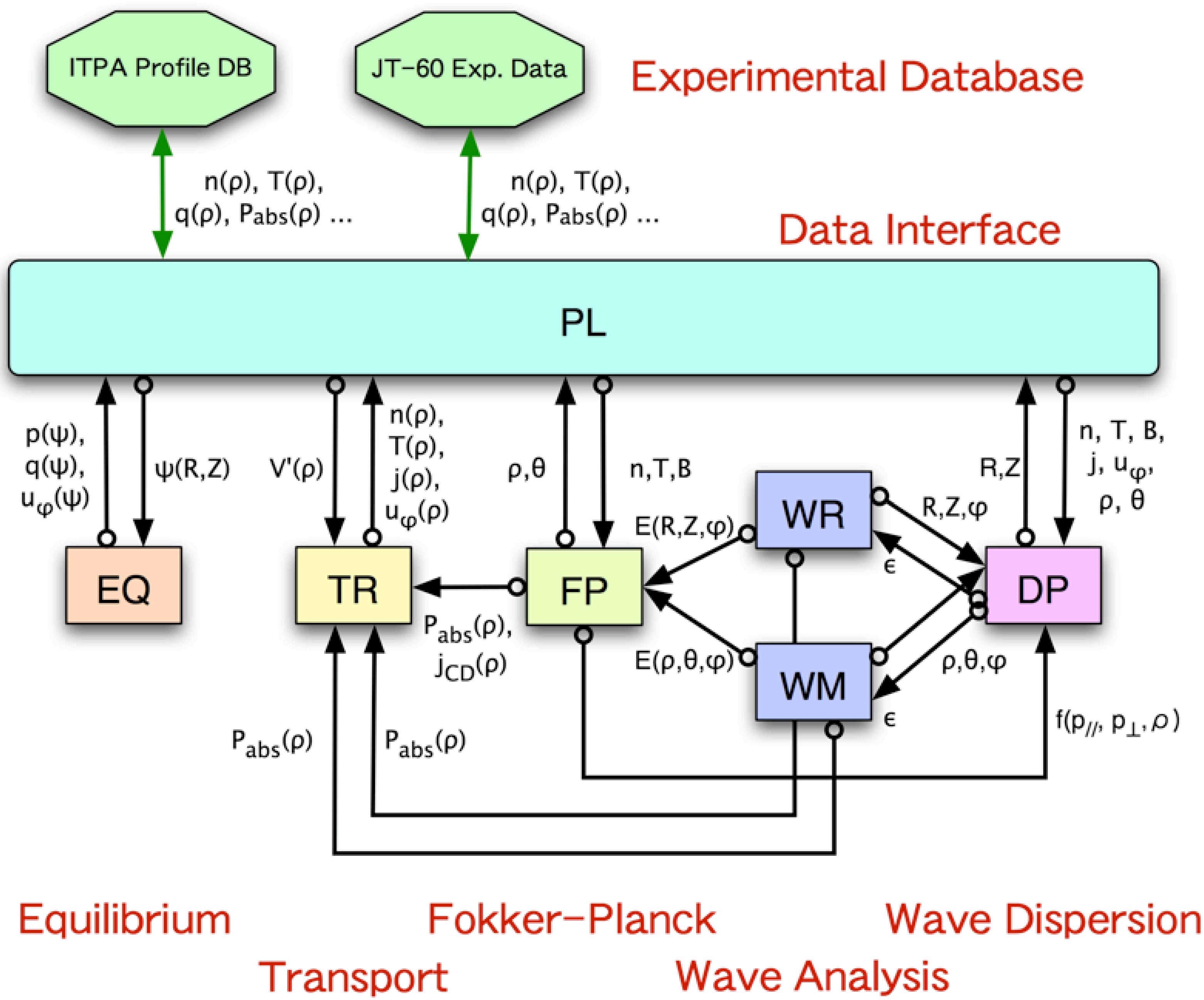
- Transport Analyzing System for Tokamak
- Modules

TASK/EQ	2D Equilibrium	Fixed boundary
TR	1D Transport	Diffusive model
TX	1D Transport	Dynamical model
FP	3D Fokker-Planck	Bounce averaged
WR	Ray/Beam Tracing	EC, LH
WM	Full Wave	IC,AE
DP	Wave Dispersion	Various models
LIB	Common Library	
PL	Data Conversion	Profile database

- Features:

  modular structure, various H&CD scheme, high portability, development using CVS, extension for helical plasmas

Structure of TASK Code



ECCD analysis : TASK/WR/FP/DP

- **Geometrical Optics: TASK/WR**
  - **Ray Tracing Method**:
    — Plane wave: beam size $d \gg \lambda$ wave length
  - **Beam Tracing Method**
    — Analysis of wave propagation with finite beam size
    — **Beam shape** : Gaussian beam

$$\boldsymbol{E}(\boldsymbol{r}) = \mathrm{Re}\left[C(\boldsymbol{r})\,\boldsymbol{e}(\boldsymbol{r})\,\mathrm{e}^{\,\mathrm{i}\,s(\boldsymbol{r})-\phi(\boldsymbol{r})}\right]$$

· C: amplitude, $\boldsymbol{e}$: polarization, $s(\boldsymbol{r}) + \mathrm{i}\,\phi(\boldsymbol{r})$: phase

$$s(\boldsymbol{r}) = s_0(\tau) + k^0_\alpha(\tau)[r^\alpha - r^\alpha_0(\tau)] + \frac{1}{2}s_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

$$\phi(\tau) = \frac{1}{2}\phi_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

· $\boldsymbol{r}_0$: position of beam axis, $\boldsymbol{k}^0$: wave number on beam axis

· **Curvature radius**: $R_\alpha = 1/\lambda s_{\alpha\alpha}$, **Beam radius**: $d_\alpha = \sqrt{2/\phi_{\alpha\alpha}}$

— **18 Ordinally Differential Equations** for r_α, k_α, $s_{\alpha\beta}$ and $\phi_{\alpha\beta}$,

Fokker-Planck Analysis : TASK/FP

- **Fokker-Planck equation** for **velocity distribution function** $f(p_{\parallel}, p_{\perp}, \psi, t)$

$$\frac{\partial f}{\partial t} = E(f) + C(f) + Q(f) + L(f)$$

  - $E(f)$: Acceleration term due to DC electric field
  - $C(f)$: Coulomb collision term
  - $Q(f)$: Quasi-linear term due to wave-particle resonance
  - $L(f)$: Spatial diffusion term

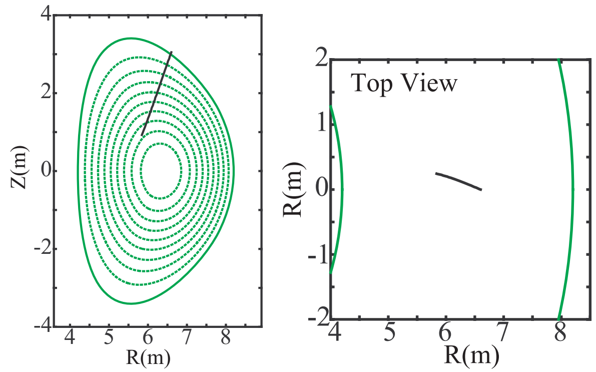
- **Bounce-averaged**: Trapped particle effect, zero banana width
- **Relativistic**: momentum $\boldsymbol{p}$, weakly relativistic collision term
- **Nonlinear collision**: momentum conservation, energy conservation
- **Three-dimensional**: spatial diffusion (classical, neoclassical, turbulence)

Wave Dispersion Analysis : TASK/DP

- **Various Models of Dispersion Tensor $\overleftrightarrow{\epsilon}(\omega, \boldsymbol{k}; \boldsymbol{r})$:**
  - Resistive MHD model
  - Collisional cold plasma model
  - Collisional warm plasma model
  - Kinetic plasma model (Maxwellian, non-relativistic)
  - Kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, non-relativistic)
  - Kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, relativistic)
  - Gyro-kinetic plasma model (Maxwellian, non-relativistic)
  - Gyro-kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, non-relativistic)
- **Arbitrary $f(\boldsymbol{v})$:**
  - Relativistic Maxwellian
  - Output of TASK/FP

Analysis of ECCD by TASK Code

Poloidal angle	70°
Toroidal angle	20°
Initial beam radius	0.05 m
Initial beam curvature	2 m

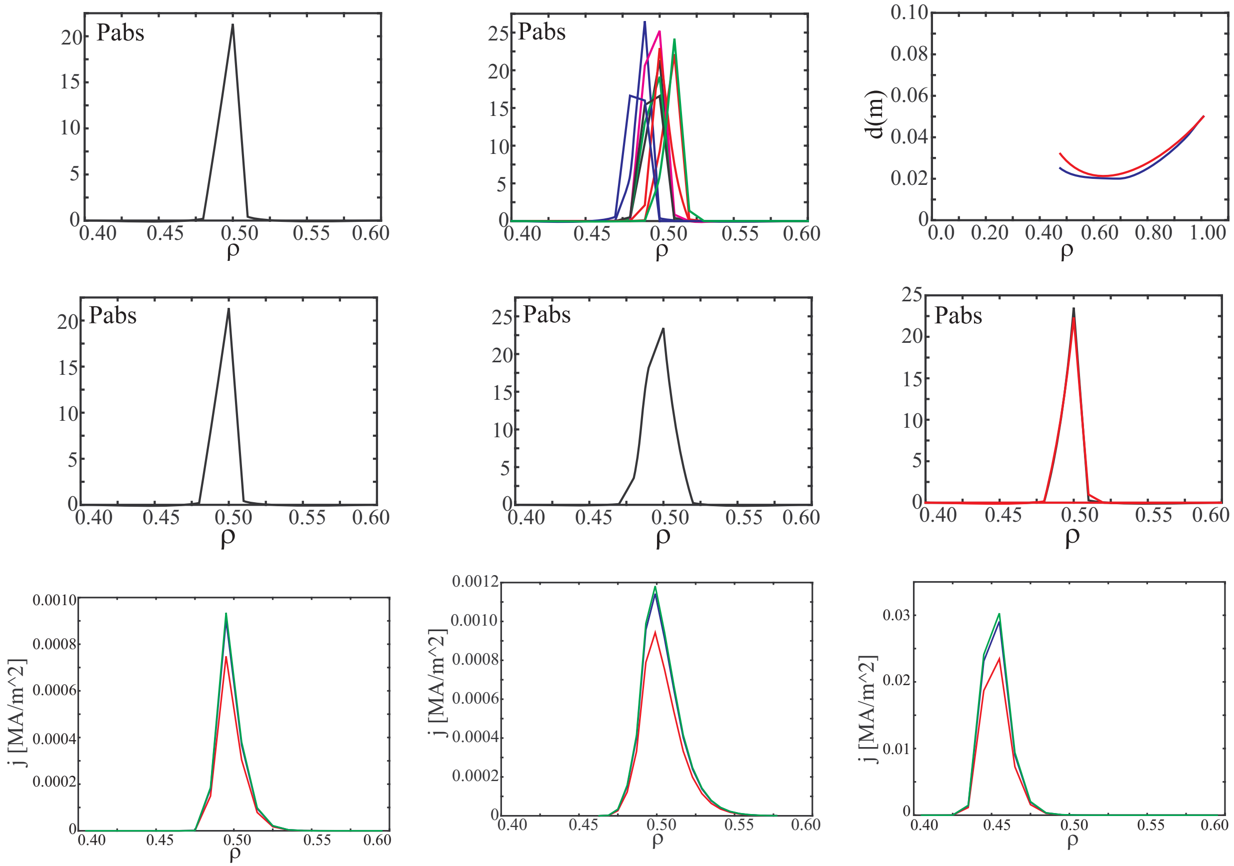


One Ray | **Multi Rays** | **Beam Tracing**

Ray/Beam Profile

P_{abs} Profile

j_{CD} Profile



Full wave analysis: TASK/WM

- **magnetic surface coordinate**: (ψ, θ, φ)
- Boundary-value problem of **Maxwell's equation**

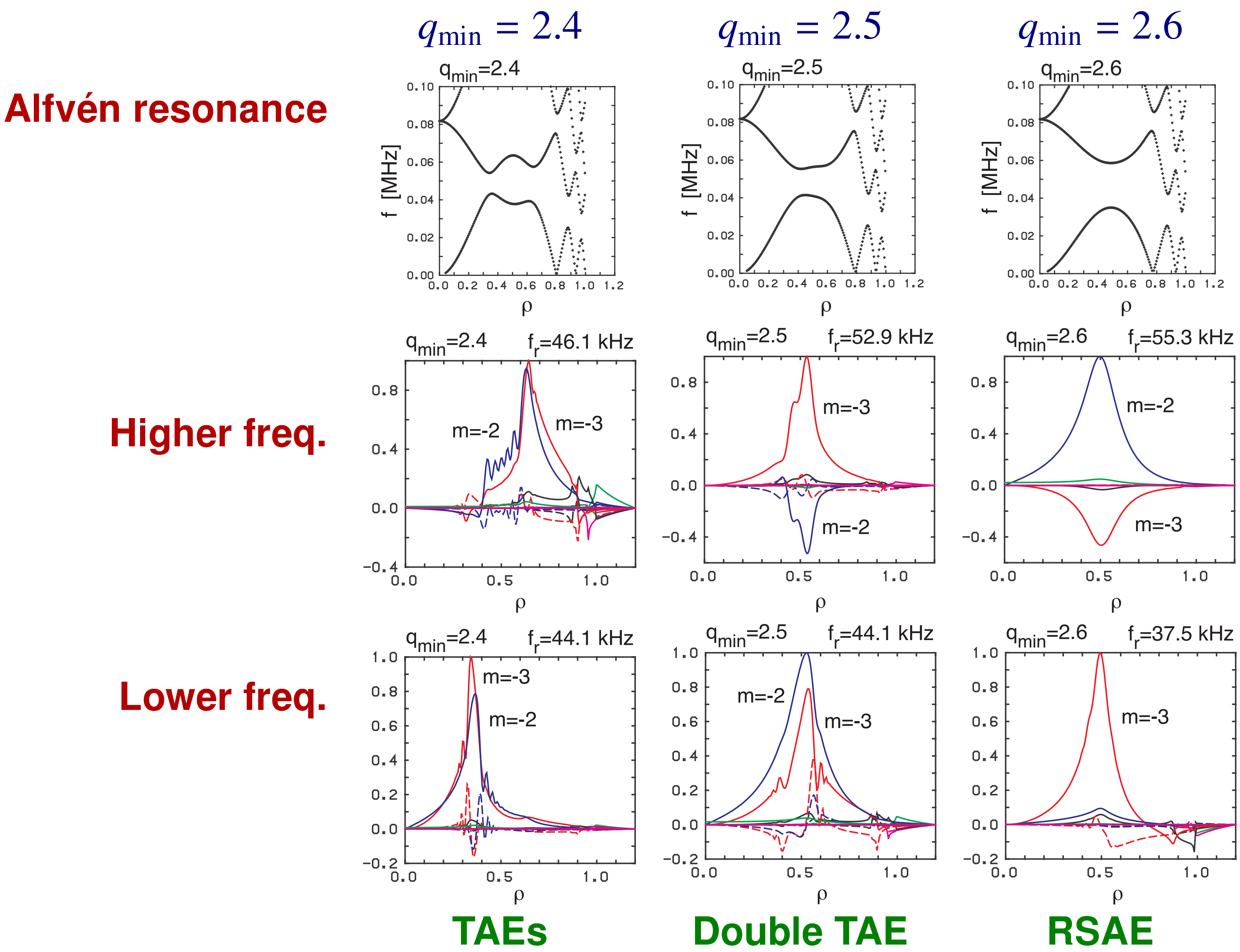
$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\, \omega \mu_0 \boldsymbol{j}_{\mathrm{ext}}$$

- Kinetic **dielectric tensor**: $\overleftrightarrow{\epsilon}$
  - **Wave-particle resonance**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\parallel} v_{\mathrm{th}}]$
  - **Fast ion: Drift-kinetic**

$$\left[\frac{\partial}{\partial t} + v_{\parallel} \nabla_{\parallel} + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \nabla + \frac{e_\alpha}{m_\alpha} (v_{\parallel} E_{\parallel} + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E}) \frac{\partial}{\partial \varepsilon} \right] f_\alpha = 0$$

- Poloidal and toroidal **mode expansion**
  - **Accurate estimation of $k_{\parallel}$**
- Eigenmode analysis: **Complex eigen frequency** which maximize wave amplitude for fixed excitation proportional to electron density

Eigenmode Structure in Reversed Shear Configuration



Excitation by Energetic Particles ($q_{min} = 2.6$)

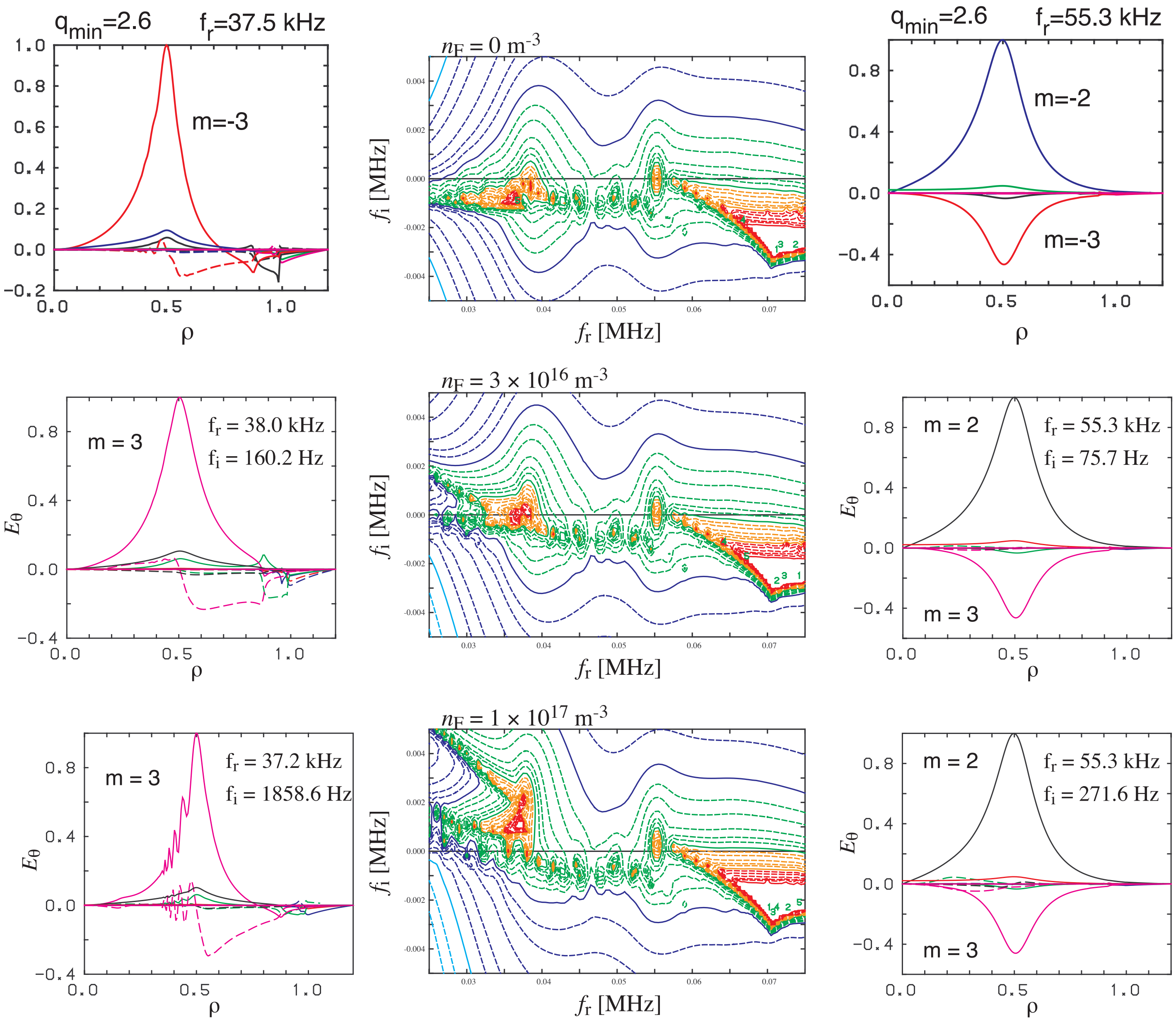
- Without EP

- With EP

  $3 \times 10^{16}\,\mathrm{m}^{-3}$
  360 keV
  0.5 m

- With EP

  $1 \times 10^{17}\,\mathrm{m}^{-3}$
  360 keV
  0.5 m



Transport Analysis

- **Level of Analysis**:
  - **TASK/TR**: Diffusive transport equation: Flux-Gradient relation
  - **TASK/TX**: Dynamical transport equation: Flux-averaged fluid equation (plasma rotation, transient phenomena)
  - **TASK/FP**: Kinetic transport equation: Bounce-averaged Fokker-Plank equation
- **Diffusive transport equation**: V: Volume, ρ: Normalized radius, $V' = \mathrm{d}V/\mathrm{d}\rho$
  - **Particle transport**

$$\frac{1}{V'}\frac{\partial}{\partial t}(n_s V') = -\frac{\partial}{\partial \rho}\left(\langle|\nabla\rho|\rangle n_s V_s - \langle|\nabla\rho|^2\rangle D_s \frac{\partial n_s}{\partial \rho}\right) + S_s$$

  - **Heat transport**

$$\frac{1}{V'^{5/3}}\frac{\partial}{\partial t}\left(\frac{3}{2}n_s T_s V'^{5/3}\right) = -\frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|\rangle \frac{3}{2}n_s T_s V_{Es} - V'\langle|\nabla\rho|^2\rangle n_s \chi_s \frac{\partial T_s}{\partial \rho}\right) + P_s$$

  - **Current diffusion**

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial}{\partial \rho}\left[\frac{\eta}{F R_0 \langle R^{-2}\rangle}\frac{R_0}{\mu_0}\frac{F^2}{V'}\frac{\partial}{\partial \rho}\left(\frac{V' B_\theta}{F}\left\langle\frac{|\nabla\rho|^2}{R^2}\right\rangle\right) - \frac{\eta}{F R_0 \langle R^{-2}\rangle}\langle \boldsymbol{J}\cdot\boldsymbol{B}\rangle_{\mathrm{ext}}\right]$$

Diffusive Transport Analysis: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**
  - **Multi thermal species**: e.g. Electron, D, T, He
    — Density, thermal energy, (toroidal rotation)
  - **Two beam components**: Beam ion, Energetic α
    — Density, toroidal rotation
  - **Neutral**: Two component (cold and hot), Diffusion equation
  - **Impurity**: Thermal species or fixed profile
- **Transport Model**
  - **Neoclassical**: Wilson, Hinton & Hazeltine, Sauter, NCLASS
  - **Turbulent**: CDBM (current diffusive ballooning mode), GLF23 (V1.61)
- **Sources**
  - Heating and current data: Interface to TASK/WR/WM/FP, Analytical
  - Simple NBI, Nuclear fusion, Ionization, Charge exchange, Radiation
- **Interface to Experimental Data**
  - UFILE

CDBM Turbulence Model

- **Marginal Stability Condition** $(\gamma = 0)$

$$\chi_{TB} = F(s, \alpha, \kappa, \omega_{E1})\, \alpha^{3/2} \frac{c^2}{\omega_{pe}^2} \frac{v_A}{qR}$$

Magnetic shear $s \equiv \dfrac{r}{q}\dfrac{dq}{dr}$

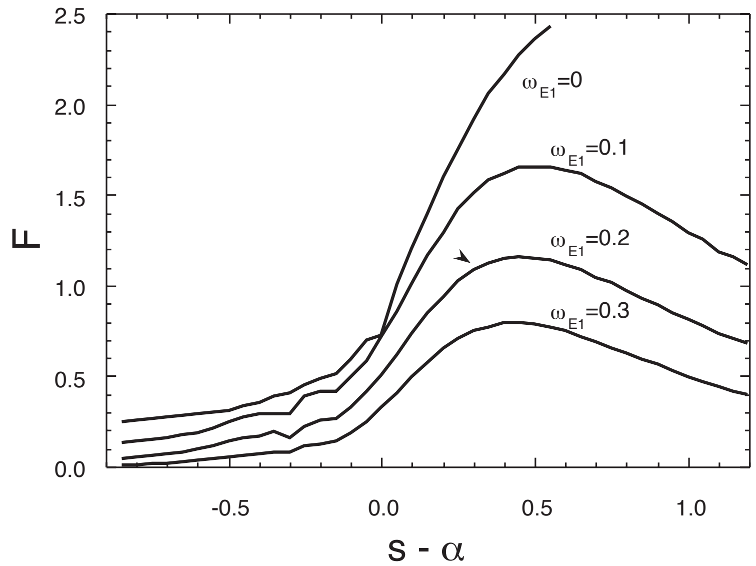
Pressure gradient $\alpha \equiv -q^2 R \dfrac{d\beta}{dr}$

Magnetic curvature $\kappa \equiv -\dfrac{r}{R}\left(1 - \dfrac{1}{q^2}\right)$

$E \times B$ **rotation shear** $\omega_{E1} \equiv \dfrac{r^2}{s v_A}\dfrac{d}{dr}\dfrac{E}{rB}$

- **Weak and negative magnetic shear, Shafranov shift and $E \times B$ rotation shear reduce thermal diffusivity.**

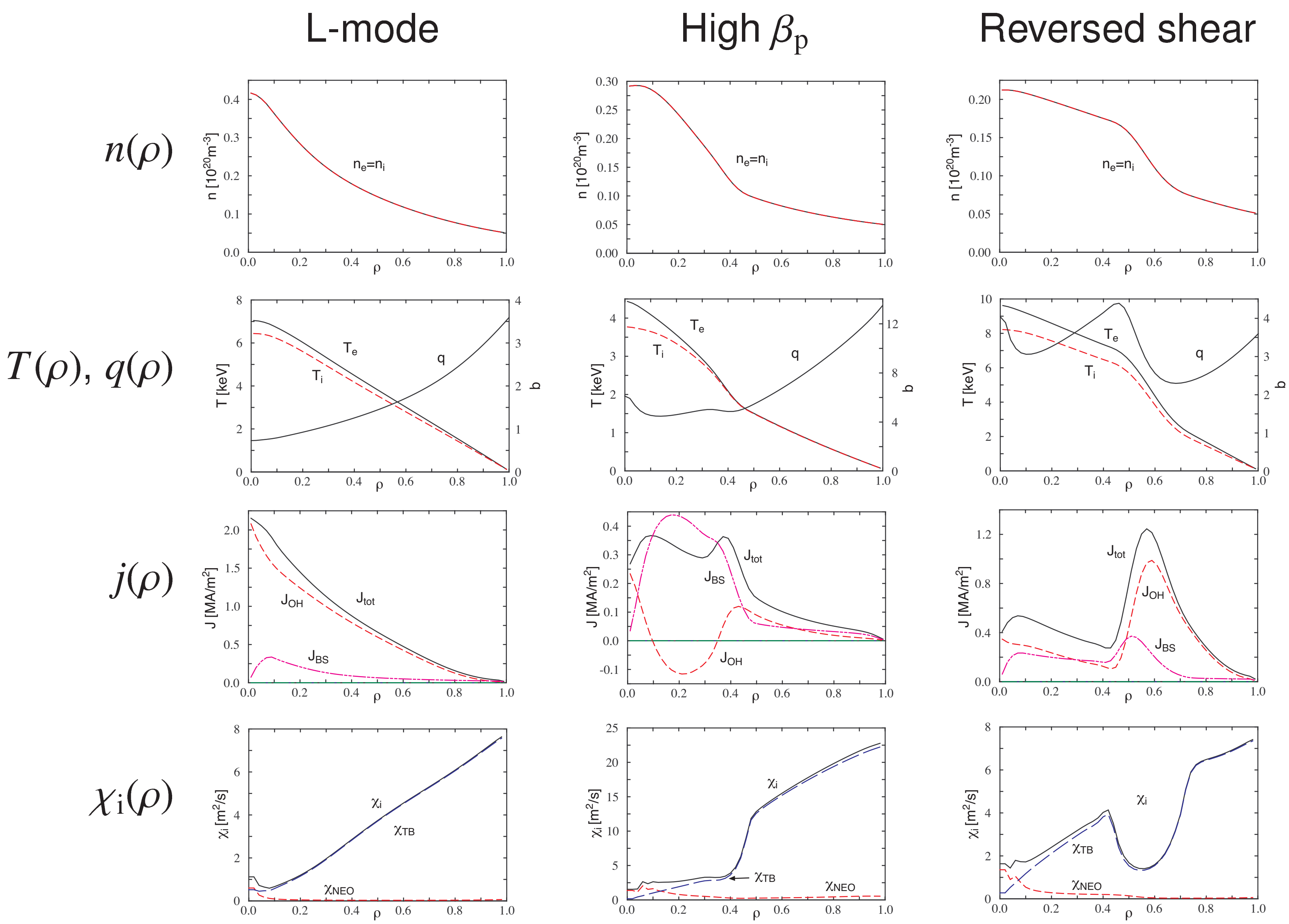
$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{E1})$



Fitting Formula

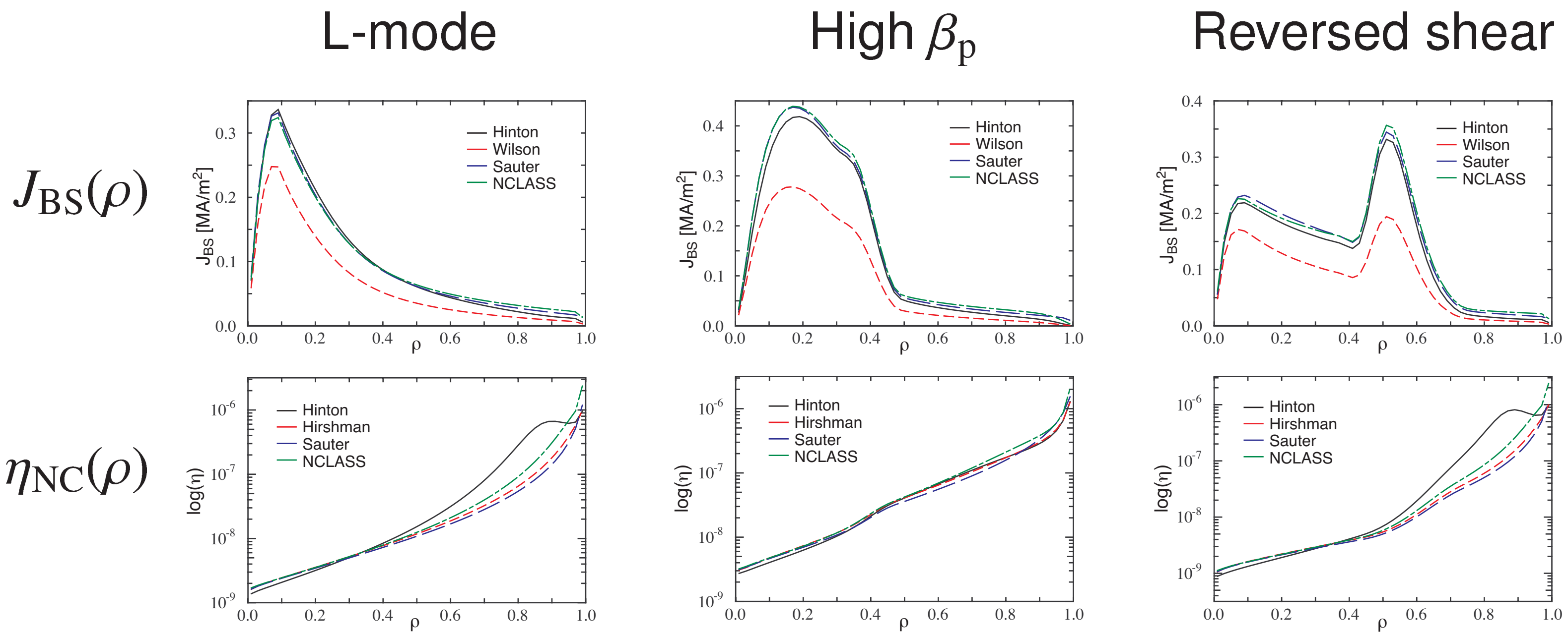
$$F = \begin{cases} \dfrac{1}{1 + G_1 \omega_{E1}^2} \dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for } s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1 + G_1 \omega_{E1}^2} \dfrac{1 + 9\sqrt{2} s'^{5/2}}{\sqrt{2}(1 - 2s' + 3s'^2 + 2s'^3)} & \text{for } s' = s - \alpha > 0 \end{cases}$$

Typical Profile



Neoclassical Transport Model

- **Comparison of Bootstrap Current and Resistivity**
  - **Wilson model**: from “Tokamaks 2nd ed” (Wesson)
  - **Hinton and Hazeltine model**
  - **Sauter model**
  - **NCLASS package** (Houlberg)

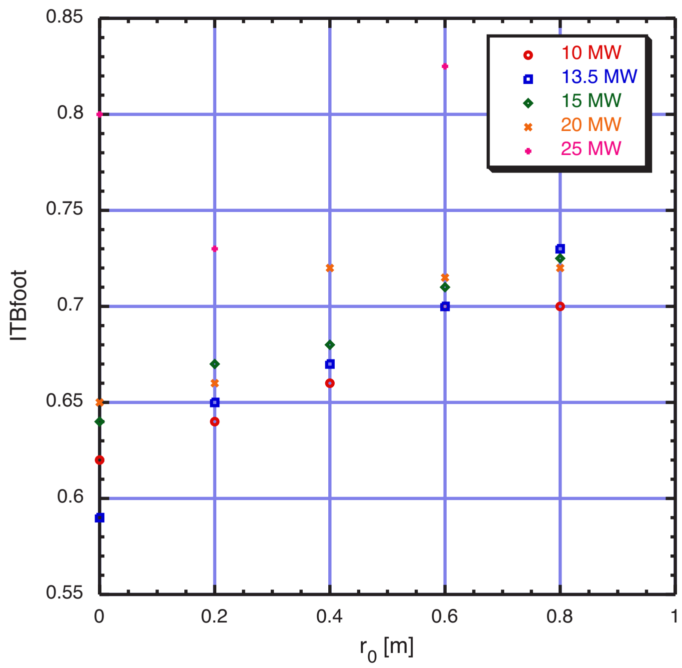


- **Fairly good agreement except Wilson model**

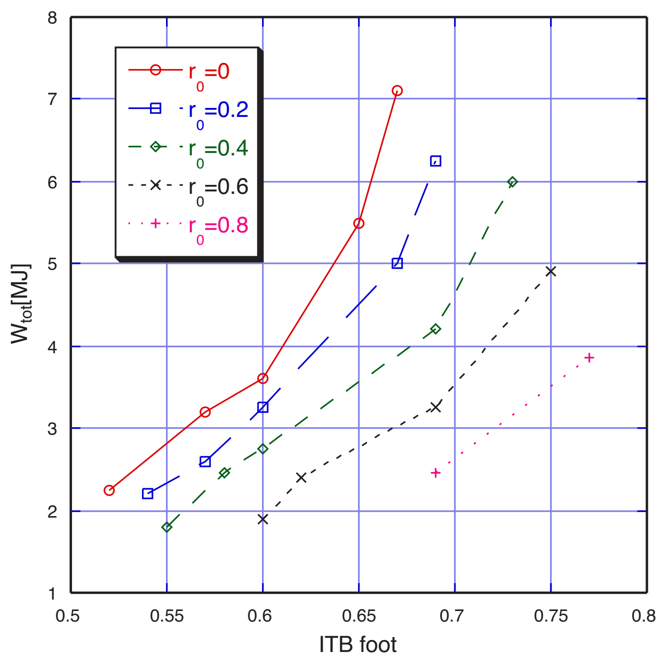
ITB Foot Location and Store Energy

- **High β_p mode**
- Heating center radius r_0 and heating power P_H are changed.
- **ITB foot location r_{foot}, Stored energy W_{store}**

r_{foot} vs r_0



W_{store} vs r_{foot}

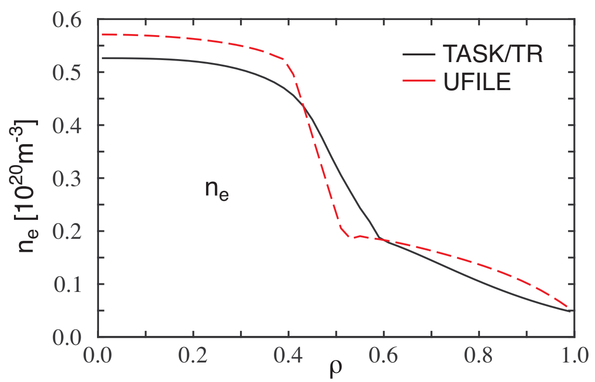


- **With the increase of P_H, r_{foot} and W_{store}** increases.
- **If P_H fixed, W_{store} decreases with the increase of r_0.**

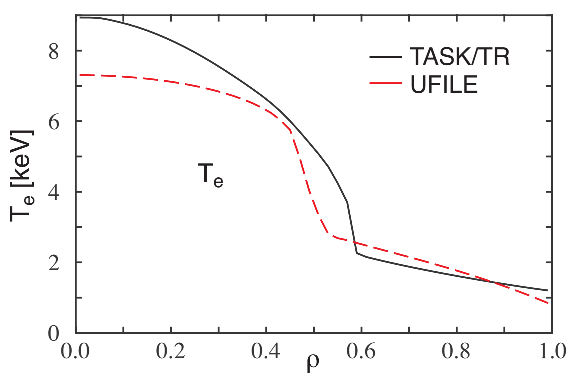
Comparison with JT-60 Experiment

- **Reversed Shear Configuration**
  - **Shot number: 29728**
  - Profiles q, P_e, P_i: given
  - Metric data: given
  - Edge density and temperature: given
  - Transport model: Sauter + CDBM(with $E \times B$ rotation)

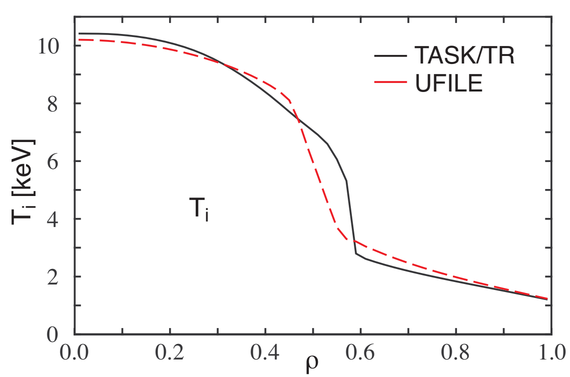
$n_\mathrm{e}(\rho)$



$T_\mathrm{e}(\rho)$



$T_\mathrm{i}(\rho)$



Comparison with JET Experiment

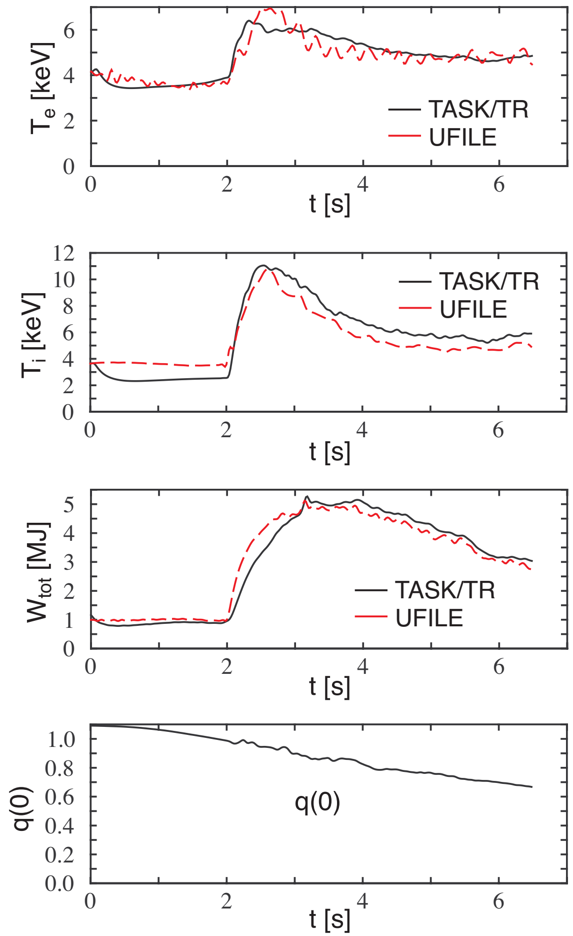
- **Shot number: 19691**

T_{e0}

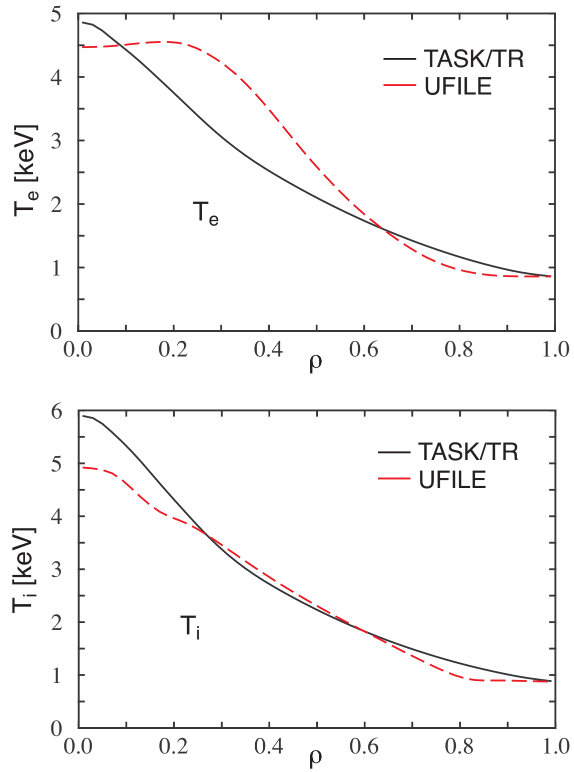
T_{i0}

W_{tot}

q_0

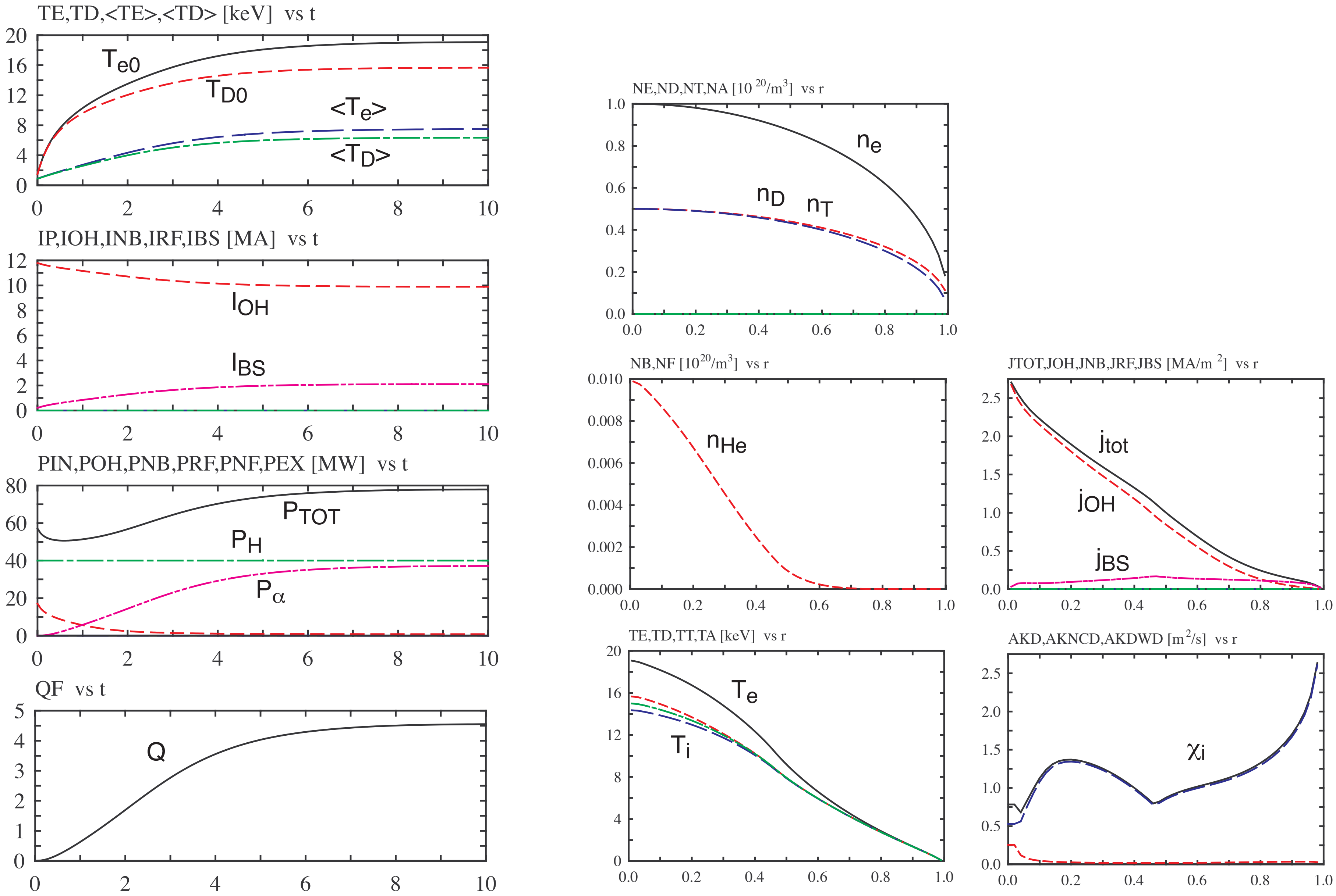


T_e and T_i



- **Sawtooth relaxation slightly improves T_e profile.**

Preliminary ITER simulation



Transport Model

- **1D Transport code (TASK/TX)** *Ref. Fukuyama et al.*
- **Two fluid equation for electrons and ions**
  - **Flux surface average**
  - **Coupled with Maxwell equation**
  - **Neutral diffusion equation**
- **Neoclassical transport**
  - **Included as a poloidal viscosity term**
  - **Diffusion, resistivity, bootstrap current, Ware pinch**
- **Anomalous transport**
  - **Current diffusive ballooning mode**
  - **Ambipolar diffusion through poloidal momentum transfer**
  - **Perpendicular viscosity**

Dynamical Transport Equation: TASK/TX

- **Bounce-averaged transport equation** (electron, ion)

$$\frac{\partial n_s}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r n_s u_{sr}) + S_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{sr}) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr}^2) + \frac{1}{r} m_s n_s u_{s\theta}^2 + e_s n_s (E_r + u_{s\theta} B_\phi - u_{s\phi} B_\theta) - \frac{\partial}{\partial r} n_s T_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{s\theta}) = -\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 m_s n_s u_{sr} u_{s\theta}) + e_s n_s (E_\theta - u_{sr} B_\phi) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^3 n_s m_s \mu_s \frac{\partial}{\partial r}\frac{u_{s\theta}}{r}\right)$$

$$+ F_{s\theta}^{\mathrm{NC}} + F_{s\theta}^{\mathrm{C}} + F_{s\theta}^{\mathrm{W}} + F_{s\theta}^{\mathrm{X}} + F_{s\theta}^{\mathrm{L}}$$

$$\frac{\partial}{\partial t}(m_s n_s u_{s\phi}) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr} u_{s\phi}) + e_s n_s (E_\phi + u_{sr} B_\theta) + \frac{1}{r}\frac{\partial}{\partial r}\left(r n_s m_s \mu_s \frac{\partial}{\partial r} u_{s\phi}\right)$$

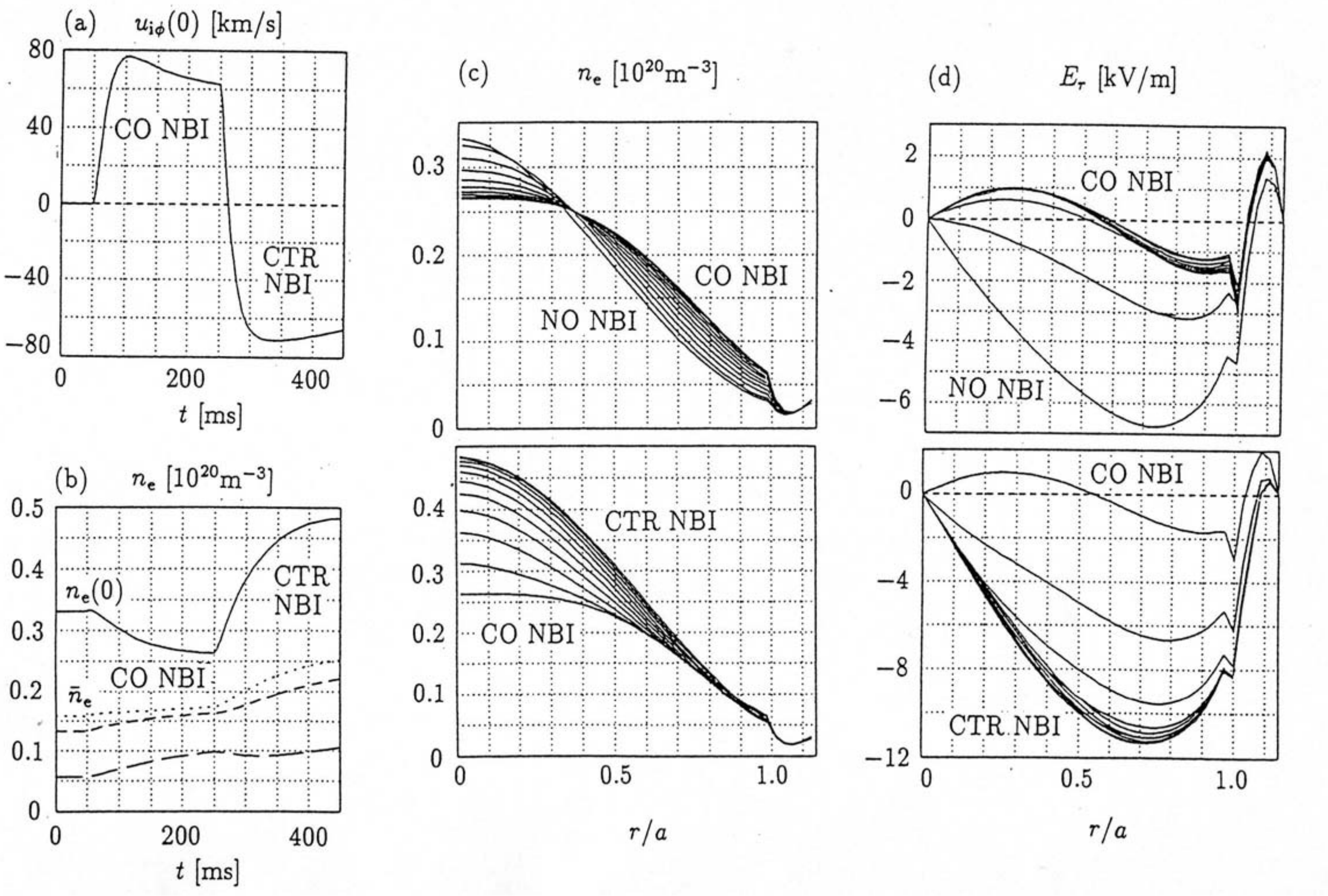
$$+ F_{s\phi}^{\mathrm{C}} + F_{s\phi}^{\mathrm{W}} + F_{s\phi}^{\mathrm{X}} + F_{s\phi}^{\mathrm{L}}$$

$$\frac{\partial}{\partial t}\frac{3}{2} n_s T_s = -\frac{1}{r}\frac{\partial}{\partial r} r\left(\frac{5}{2} u_{sr} n_s T_s - n_s \chi_s \frac{\partial}{\partial r} T_{\mathrm{e}}\right) + e_s n_s (E_\theta u_{s\theta} + E_\phi u_{s\phi})$$

$$+ P_s^{\mathrm{C}} + P_s^{\mathrm{L}} + P_s^{\mathrm{H}}$$

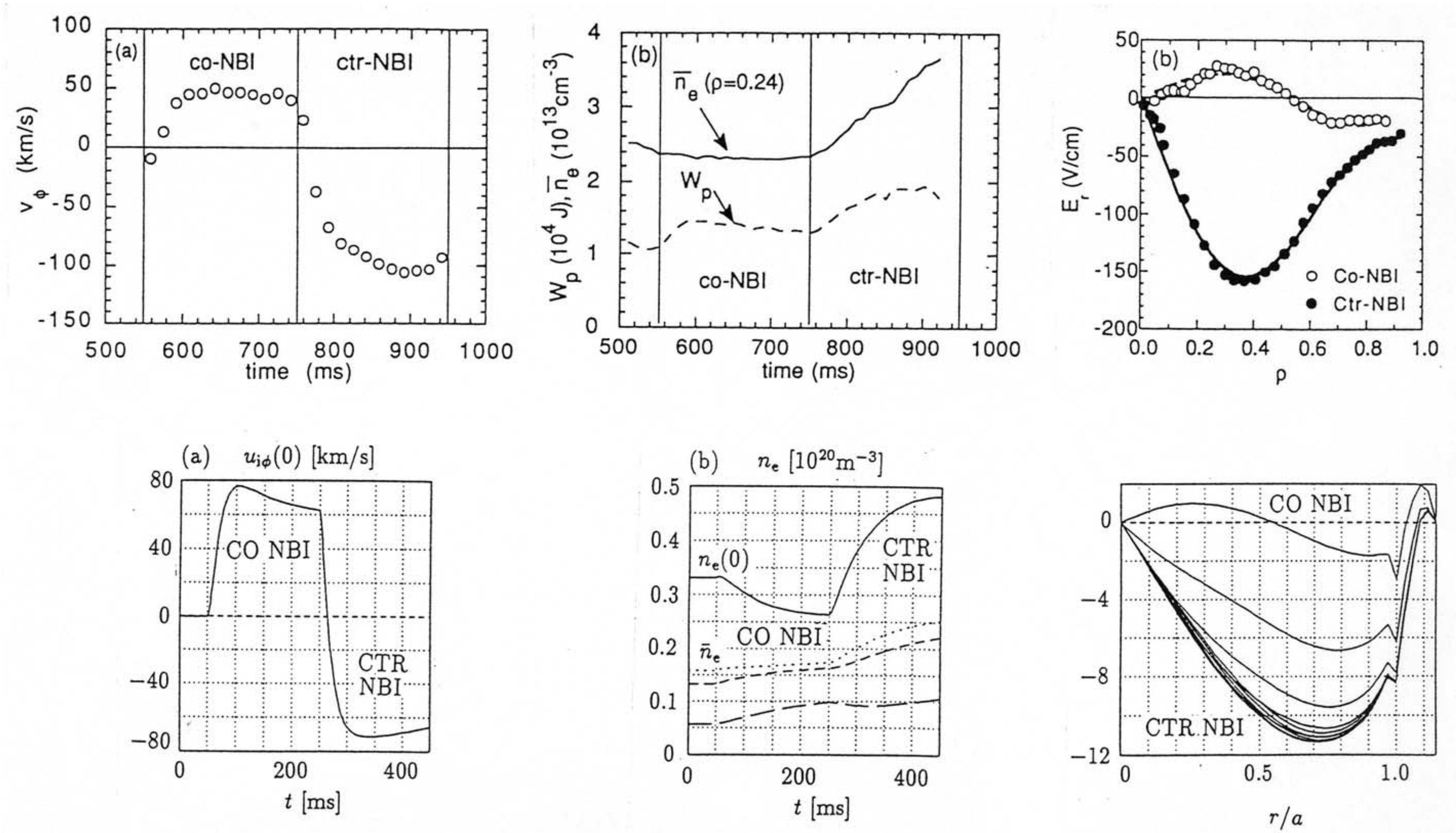
Simulation of plasma rotation and radial electric field

- **JFT-2M parameter**: NBI co-injection $\longrightarrow$ counter-injection
- Toroidal rotation $\Longrightarrow$ Negative E_r $\Longrightarrow$ Density peaking
- **TASK/TX**: Particle Diffusivity: $0.3\,\mathrm{m^2/s}$, Ion viscosity: $10\,\mathrm{m^2/s}$



Comparison with JFT-2M Experiment

- **JFT-2M Experiment**: **Ida et al.: Phys. Rev. Lett. 68 (1992) 182**
- Good agreement with experimental observation



Summary

- We are developing TASK code as a reference core code for burning plasma simulation based on transport analysis.
- The TASK code is composed of modules: equilibrium, transport, wave analysis, velocity space analysis, and data interface.
- Comparison of the results of TASK/TR and TASK/TX with experimental observation is ongoing for several transport models. Preliminary example of ITER burning plasma was also presented.
- To Do
  - Standard data interface with other simulation code
  - Systematic comparison with experimental data
  - Improvement of modules and development of new modules